# Observations over hurricanes from the ozone monitoring instrument

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[1] There is an apparent inconsistency between the total column ozone derived from the total ozone mapping spectrometer (TOMS) and aircraft observations within the eye region of tropical cyclones. The higher spectral resolution, coverage, and sampling of the ozone monitoring instrument (OMI) on NASA's Aura satellite as compared with TOMS allows for improved ozone retrievals by including estimates of cloud pressure derived simultaneously using the effects of rotational Raman scattering. The retrieved cloud pressures are more appropriate than the climatological cloud-top pressures based on infrared measurements used in the TOMS and initial OMI algorithms. We find that total ozone within the eye of hurricanes Katrina and Rita is significantly overestimated when we use climatological cloud pressures. The cloud-corrected total ozone is in better agreement with aircraft measurements that imply relatively small or negligible amounts of stratospheric intrusion into the eye region. **Citation:** Joiner, J., A. Vasilkov, K. Yang, and P. K. Bhartia (2006), Observations over hurricanes from the ozone monitoring instrument, *Geophys. Res. Lett.*, *33*, L06807, doi:10.1029/2005GL025592.

## 1. Introduction

[2] Satellite measurements of the total column ozone have been used to constrain conceptual models of tropical cyclone dynamics and monitor the upper-tropospheric and lower-stratospheric circulation in tropical cyclones [e.g., *Stout and Rodgers*, 1992]. One element of a conceptual model developed by *Rodgers et al.* [1990] is enhanced total ozone in the eye region of tropical cyclones resulting from stratospheric intrusion of ozone-rich air. *Zou and Wu* [2005] found that total ozone from the Earth Probe Total Ozone Mapping Spectrometer (TOMS) was elevated by ~30 Dobson units (DU) or ~10% in the eye of hurricane Erin relative to the area outside the eye. However, these TOMS observations appear to be at odds with more recent aircraft measurements that do not support significantly enhanced ozone amounts in the eye region of tropical cyclones owing to stratospheric subsidence.

[3] One problem with backscatter UV measurements, such as those from TOMS, is that in the presence of thick clouds, ozone beneath the clouds is shielded from the satellite. The TOMS Version 8 (V8) data set includes both the total column ozone retrieved above the cloud and an calculated "hidden" amount below. Both quantities require an estimate of cloud pressure. TOMS V8 uses a climatological cloud pressure data set based on infrared measurements.

[4] The ozone monitoring instrument (OMI) [*Levelt et al.*, 2006], currently flying on NASA's Earth Observing System (EOS) Aura satellite, has higher spatial resolution than TOMS in the majority of its swath. OMI also has higher spectral resolution and significantly more spectral coverage than TOMS. The latter allows for retrievals of cloud pressure that can be used to accurately derive the above-cloud ozone as well to estimate the hidden ozone below clouds [*Vasilkov et al.*, 2004].

[5] In order to resolve the apparent discrepancy between TOMS total ozone and aircraft measurements within the eye region of tropical cyclones, we first review the existing aircraft observations to place them in context with TOMS and OMI retrievals. We then examine total ozone from OMI over hurricanes Katrina and Rita at their peak intensities. Specifically, we show total column differences that result from replacing the IR-based climatological cloud-top pressures with those retrieved from OMI.

## 2. Review of Aircraft Ozone Measurements

[6] The first in situ measurements of ozone within a tropical cyclone were made from a U-2 plane at pressures between 50 and 300 hPa in hurricane Ginny [*Penn*, 1965]. From the cloud top pressure of 200 hPa to near the tropopause at ~120 hPa, ozone mixing ratios were elevated by ~40% as compared with surrounding environment ~8–72 km distant. These measurements have been used to substantiate elevated amounts of total ozone from TOMS within the eye region of tropical cyclones [e.g., *Zou and Wu*, 2005]. However, the horizontal temperature gradient was essentially zero just above the cloud tops. The temperatures are therefore not consistent with hurricane-induced subsidence in the eye at and just below the tropopause. During the flight, Ginny was a weak category 1 storm with a central pressure of 989 hPa.

[7] A subsequent U2 flight over hurricane Isbell [*Penn*, 1966] showed no significant horizontal variation in ozone mixing ratios or temperature from the lower stratosphere to just below the tropopause at ~100 hPa. Thick clouds were reported in the eye from ~10 km up to the tropopause, indicating that subsidence within the eye was negligible at these altitudes. During the flight, Isbell was at category 3 strength with a central pressure of 964 hPa.

[8] *Newell et al.* [1996] describe an extensive set of measurements of ozone and other tracers from the NASA DC-8 aircraft in the eye and surrounding typhoon Mireille. When the DC-8 encountered the eye, Murielle was at or near category 2 strength and weakening. Lidar cross sections of ozone above and below the aircraft did not provide any evidence for significant entrainment of stratospheric air into the eye. However, they did show an example of a

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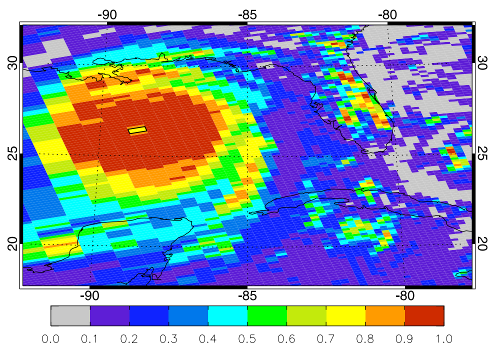


**Figure 1.** OMI 394.1 nm reflectivity ($R$) over Katrina. Pixels covering the eye ($R$ < 0.8) are outlined in black.

possible small scale intrusion of stratospheric air into the upper troposphere. Lidar-derived ozone values in the lower troposphere were consistent with low surface values measured as Mireille passed over Oki Island. The authors suggested that the central eye region may act like a Taylor column which could transport air directly from low latitudes. The implications of the tracer data including ozone and dimethylsulfide (DMS) strongly suggest transport of marine boundary layer air to the upper troposphere in the wall cloud region and subsequent mixing into the eye with a small amount of subsidence.

[9] *Carsey and Willoughby* [2005] report ozone measurements during eyewall transects of hurricanes Georges and Floyd that further support only small amounts of stratospheric entrainment. They found relatively low concentrations of ozone in the eyewalls of intensifying hurricanes in the middle to lower troposphere and concentrations in the center of the eye near the local environmental values. As the storms weakened, they report lower ozone concentrations in the eye as compared with environmental values. During intensification, they attribute most of the air in the eye center to the eyewall <1 km above the aircraft and only as much as ∼10–20% to the tropopause.

## 3. OMI Retrieval Algorithms

[10] OMI is a hyperspectral imager with dual grating spectrometers (UV and VIS channels) that employ CCD detectors. One of the two UV subchannels (UV-2) covers 310–365 nm while VIS ranges from 365 to 500 nm. The swath width is nominally 2600 km with a ground pixel dimension of ∼13 × 24 km at nadir and a larger size at the swath edge. The average spectral resolutions (FWHM) are 0.45 nm (UV-2) and 0.63 nm (VIS).

[11] To facilitate the analysis of ozone fields, the satellite-derived column ozone values are usually normalized to the surface pressure. In this paper, for clarity, we normalize with respect to the climatological surface pressure. This is done even when clouds are present, and satellite instruments such as OMI measure ozone only above the cloud. This normalization requires an estimate of cloud pressure in order to compute the hidden column ozone beneath clouds. Therefore, if we overestimate cloud altitude, we also overestimate the ozone column below cloud and vice-versa.

[12] In TOMS and OMI V8, there are additional cloud pressure-related errors that affect the ozone retrieval above cloud. These include 1) error in estimating multiple scattering between cloud and overlaying atmosphere 2) errors in estimating the effects of rotational Raman scattering (RRS) and $O_2$-$O_2$ absorption and 3) errors in the application of the aerosol correction. Over very bright clouds, the combined effect of these errors can be as large as 20 DU. This adds to errors in the estimated ozone below cloud producing errors in the total column of 30 DU or more.

[13] The retrieval of cloud pressure can be performed with OMI using approaches based on RRS or absorption in the $O_2$-$O_2$ band near 477 nm [*Acarreta et al.*, 2004]. Both techniques rely on the property that clouds screen the atmosphere below from satellite observations. Clouds similarly shield tropospheric ozone from UV remote-sounding instruments. Therefore, the use of cloud pressures derived with these approaches provides accurate estimates of both above- and below-cloud column ozone. Here we use cloud pressures from the RRS approach [*Joiner and Vasilkov*, 2006]. Cloud pressure is determined from the filling-in of two strong Ca Fraunhofer lines due to atmospheric RRS using a fitting window between 392 and 398 nm.

[14] The OMI cloud pressure and ozone retrieval algorithms make use of the Lambert-equivalent reflectivity (LER) concept. The LER model treats a cloud or ground as a horizontally homogeneous opaque Lambertian-reflecting surface defined by its reflectivity ($R$) and an effective pressure ($P_{LER}$). The LER accounts for the effects of aerosol and cloud scattering and can include light reflection from the ground if the clouds are semi-opaque. $P_{LER}$ is representative of pressures reached by back-scattered photons averaged over a weighting function. Therefore $P_{LER}$ can account for the effects of scattering or absorption within and below clouds by having a pressure greater than the cloud top.

[15] The currently-released OMI total ozone retrievals are based on the TOMS V8 [*Bhartia and Wellemeyer*, 2002]. TOMS and OMI V8 both use a cloud pressure climatology that was produced with coincident measurements from the Nimbus 7 TOMS and the temperature humidity infrared radiometer (THIR). The THIR-derived cloud-top pressures with high TOMS UV reflectivity were mapped onto a monthly 2.5 × 2.5° grid. The OMI V8 algorithm can alternatively use OMI RRS-derived cloud pressures.

## 4. OMI Results and Discussion

[16] Figures 1 and 2 show the OMI 394.1 nm reflectivity (LER) and effective cloud pressures ($P_{LER}$), respectively,

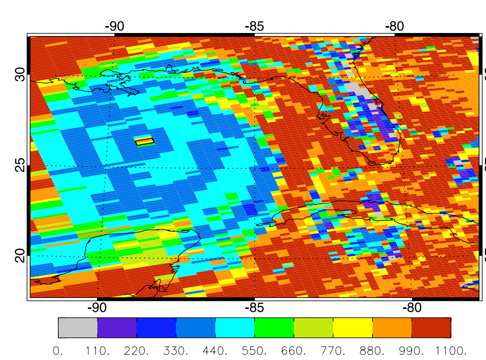


**Figure 2.** As in Figure 1 but OMI cloud pressure $P_{LER}$ (hPa).

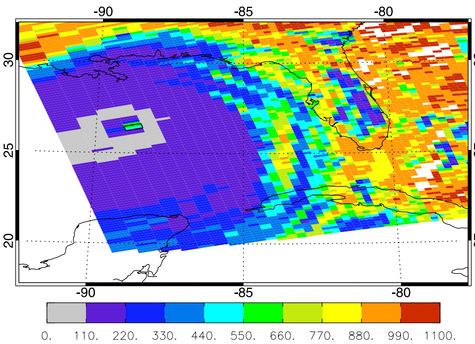


**Figure 3.** As in Figure 1 but MODIS cloud-top pressure (hPa).

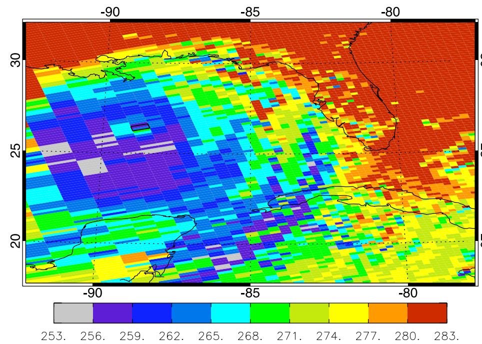


**Figure 5.** As in Figure 4 but total column ozone (DU) retrieved with OMI RRS cloud pressures.

over hurricane Katrina for orbit 5963 on 28 August 2005. The overpass time was ~18:48 UT when Katrina was at category 5 strength with a central pressure of 906 hPa. Extremely high reflectivities (>90%) can be seen extending radially for distances of ~200 km from the center. The eye has distinctly lower reflectivity than the surrounding area, but the absolute reflectivity remains high (~70%). Visible imagery showed a distinct eye that was significantly cloud-filled. A secondary cloud wall is apparent in $P_{\mathrm{LER}}$ that is not evident in the reflectivity map.

[17] Cloud-top pressures from the EOS Aqua Moderate-Resolution Imaging Spectroradiometer (MODIS) level 2 collection 4 [*Platnick et al.*, 2003] are shown in Figure 3. OMI and MODIS are part of the so-called A-train satellites flying in formation within 30 minutes of each other. The MODIS retrievals use the $CO_2$ slicing method that is sensitive to the highest cirrus clouds.

[18] *Joiner et al.* [2004] showed that UV light can penetrate through thin or even moderately thick cirrus clouds to lower water clouds. The OMI RRS algorithm therefore retrieves an effective LER pressure more representative of a lower cloud deck [*Joiner and Vasilkov*, 2006]. Over Katrina, MODIS reports higher clouds than OMI both inside and outside the eye. Inner cloud bands seen in the OMI $P_{\mathrm{LER}}$ are somewhat obscured by cirrus in the MODIS image.

[19] Concurrent estimates of cloud liquid water and ice profiles from the tropical rainfall measurement mission (TRMM) microwave imager (TMI) based on *Kummerow et al.* [1996] clearly show a secondary cloud wall that, like the primary eyewall, contains ice clouds at high altitudes and water clouds below. The derived cloud profiles therefore qualitatively support the horizontal structure in the OMI image and the difference between the OMI and MODIS cloud pressures.

[20] The choice of a cloud pressure data set has a significant impact on the retrieved total column ozone over Katrina as shown in Figures 4 and 5. Retrievals with climatological pressures show a "false eye" of enhanced total ozone coinciding with the cloud-defined eye. The false eye disappears and total ozone outside the eye is lower by ~5–10 DU when we use OMI RRS cloud pressures in the retrievals. In the central eye pixel, the climatological(RRS) cloud pressure is 307(843) hPa. The correction to the total column using RRS cloud pressures is 34 DU split almost evenly between the above- and below-cloud components.

[21] Figures 6 and 7 similarly show RRS cloud pressures and cloud-corrected ozone over hurricane Rita. The Rita images are for 21 September 2005, orbit 6313 with an equator crossing time of 19:29 UT. At this time, Rita was at or near category 5 and continuing to strengthen.

[22] Cloud pressures from OMI are again significantly higher than those from MODIS (not shown), but the features differ somewhat from Katrina. Clouds in the eyewall and outer cloud band produce lower LER pressures and there are fewer spiraling cloud bands. Elevated values of total ozone over the cloud-defined eye are again not present when RRS cloud pressures are used. The cloud correction for total ozone in the eye pixel was ~20 DU for Rita.

[23] We examined data over Katrina, Rita, and Wilma on other days. Unfortunately, storm placement was frequently

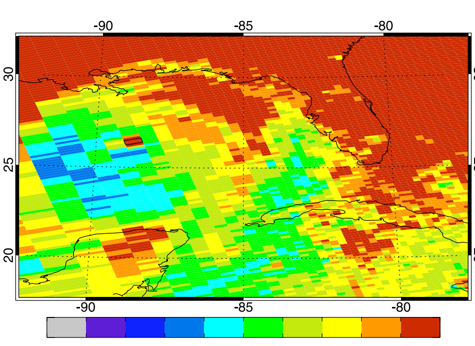


**Figure 4.** Total column ozone (DU) retrieved with climatological cloud pressures. To focus on the immediate vicinity of Katrina, values above 280 DU are shown in red.

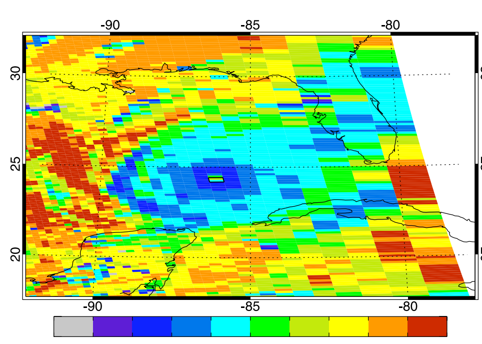


**Figure 6.** As in Figure 2 but $P_{\mathrm{LER}}$ (hPa) over Rita.

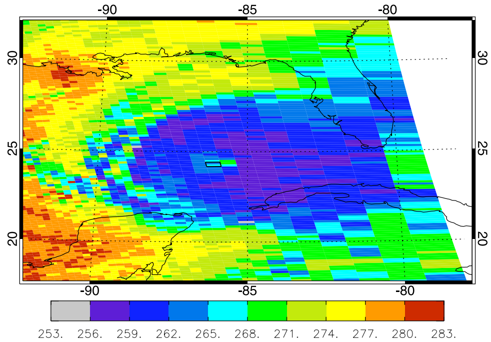


**Figure 7.** As in Figure 5, but corrected total ozone over Rita.

near the OMI swath edge and features were not as well resolved as in the images shown here.

[24] *Newchurch et al.* [2001] examined the effect of cloud pressure errors on the TOMS V7 total ozone algorithm. They postulated that in high tropical convective clouds, the climatological cloud pressures were too low in altitude resulting in an underestimate of total ozone. However, we find over Katrina and Rita that the opposite is true, and that total ozone is overestimated when using the cloud climatology.

[25] Although the cloud-corrected total column ozone in the cloud eye is similar to surrounding values outside the eye, Figures 5 and 7 show a few pixels with somewhat elevated total ozone (5–10 DU) slightly displaced from the cloud-defined eye. In both Katrina and Rita, the displacements are oriented toward the regions with the lowest ozone amounts. These are statistically significant enhancements in total ozone. They may be explained by stratospheric intrusion, most likely only into the upper troposphere as in the lidar observations of *Newell et al.* [1996]. Note that these images were taken over hurricanes that were at higher intensities than the high altitude aircraft measurements discussed above.

[26] Another interesting feature is that the spiraling bands of low total ozone do not always coincide exactly with the position of the higher clouds associated with outer rain bands. The regions of low total ozone amounts most likely contain air of marine boundary layer origin transported upward in the rain bands as in observed by *Carsey and Willoughby* [2005]. The low ozone air may then become slightly displaced in the horizontal with respect to the cloud bands. *Carsey and Willoughby* [2005] found regions of warm, dry air with elevated ozone mixing ratios that they interpreted as dry mesoscale downdrafts. Such regions are also evident in the Katrina and Rita total ozone images.

## 5. Conclusions and Ongoing Work

[27] The inconsistency between TOMS V8-derived total column ozone and aircraft observations in tropical cyclone eye regions is largely explained by TOMS errors associated with using incorrect cloud pressures. Errors in the estimated total column ozone can be >∼30 DU or approximately 10% for high reflectivity scenes. When OMI-V8 total ozone is corrected using RRS cloud pressures, elevated values in the cloud-defined eyes of Katrina and Rita disappear. We are currently conducting a detailed assessment of the effect of cirrus over water clouds on the derivation of total ozone from OMI using RRS-derived cloud pressures. We will include cloud-corrected total ozone in a future release of OMI total ozone data. Finally, we plan to further examine OMI data during the evolution of tropical cyclones.

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